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Core, Mantle, Crust: Imaging the Earth's Interior with Ultra-High Energy Neutrino Tomography

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Abstract

We report on the feasibility of using an isotropic flux of cosmic neutrinos in the energy range of 10 to 10,000 TeV to study the interior geophysical structure of the Earth. The angular distribution of events in a $\sim \mathrm{km}^3$-scale neutrino telescope can be inverted to yield the Earth's nucleon density distribution. The approach is independent of previous seismic methods. The energy spectrum of the neutrino primaries can also be determined from consistency with the angular distribution. Depending on neutrino flux, a reasonable density determination can be obtained with a few hundred receivers operating for a few years.

1 Introduction:

The character of the Earth's interior remains a fascinating subject. The density profile has been deduced only indirectly by methods with model-dependence. We report on a novel way to create a direct 'snapshot' of the nucleon density from core to crust, by exploiting tomography with ultra-high energy neutrinos of cosmic origin (Jain, Ralston and Frichter 1999). We assume there exists a reasonably isotropic source of ultra-high energy (UHE) neutrinos from cosmological sources. The possible sources include unresolved active galactic nuclei, gamma ray bursts, secondary emissions from cosmic rays, *etc*.

Neutrino Tomography exploits the information in the observed *angular distribution*. After passing through the Earth, the surviving neutrino flux Φ_ν measured at nadir angle θ is given by

$$\Phi_{\rm surv}(E,\theta) = \Phi_\nu(E) e^{-\sigma_{\rm eff}(E) R n(R) f(\theta)} \,, \tag{1}$$

where R is the Earth's radius and the function $f(\theta)$ is proportional to the integrated nucleon density along the chord $0 < z < 2R\cos(\theta)$. Using the absorption cross section $\sigma_{\rm eff}(E)$ from particle physics (Frichter *et al* 1995, Gandhi *et al* 1998), there is enough information in $\Phi_{\rm surv}(E,\theta)$ to invert an integral transform, yielding the nucleon density. Thus our approach differs fundamentally from previous studies concentrating on exploiting point neutrino sources (Kuo *et al* 1995, and references therein). An advantage of our approach is that the "whole sky" is used as a source for tomography. In addition, the statistical cost of binning events periodically in time required for point sources is eliminated. As a result the results appear promising.

Event rates scale with the primary fluxes. Our method is not overly dependent on flux estimates: The flux normalization is actually irrelevant, and only contributes to the statistical errors. We use fluxes consistent with current estimates and their updated normalizations (Stecker *et al* 1992, Szabo and Protheroe 1994, Protheroe and Szabo 1992). Event rates also scale with detector size, and detection efficiency in the relevant energy range. We focus on future experiments with a detection volume of order 1 km^3 (KM3). We use Monte Carlo simulations of the RICE pilot experiment currently running in conjunction with AMANDA at the South Pole. The RICE project (Frichter *et al* 1996a, Frichter *et al* 1996b) uses coherent radio emission from neutrino-induced electromagnetic showers, which is the most efficient known method for neutrino energies of roughly 100 TeV and above. Radio detection is not mandatory, of course, and any method generating comparable statistics and angular pointing accuracy should work as well.

The energy dependence of the primary neutrino flux is also determined by the procedure. This is unexpected and welcome. Energy determination occurs because the interaction cross section and detector efficiencies are

energy dependent. (Both the interaction cross section and the detector efficiency rise like a power of energy. These tend to compensate the fall of flux with energy, yielding a comparatively flat, broad dominant region of 1-10 PeV primary neutrino energy.) To exploit this we first need a well determined angular distribution integrated over energy. We also need initial data, which we realistically assume is poorly determined, on the energy spectrum integrated over angle. Our procedure then alternately iterates the energy spectrum and density to obtain consistency with the angular spectrum. At no point is the joint energy and angular distribution needed.

For a wide range of trial density distributions the procedure converges within about five iterations. Thus by consistency of iteration the angular distribution eventually determines the energy spectrum. The energy spectrum obtained this way may serve as a method to measure the incident energy spectrum.

If one assumes that the density profile of the Earth is already well known, then the angular distribution strongly overdetermines the problem. This is quite interesting. One might even be able to deduce the energy dependence of the neutrino-nucleon total cross section. There is an opportunity, then, to explore fundamental features of particle physics which have never been directly measured. While the predictions of small-x QCD are thought to be reliable in this region, there are various reasons (Ralston *et al* 1996b) why direct verification is desirable, and might yield new physical information.

2 Results and Discussion:

One boundary condition must be fixed in order to obtain convergence and a unique solution. The boundary condition is taken to be the value of the density of the Earth near the surface. Since the surface density is known with reasonable accuracy, the boundary condition is not a cause of substantial uncertainty. The simulations used the Preliminary Earth Reference Model (PREM) for the Earth's density profile (see Jain, Ralston and Frichter 1999 for details). Two moments of the density are well known: These are the total mass of the Earth (just as Cavendish used), and the Earth's moment of inertia. But the entire procedure can be carried out (as we did) without making use of these moments, so in practice the density we find is over-determined.

We employed a generic form of the diffuse AGN neutrino flux, $\Phi_\nu(E) = \Phi_o E^{-2}$ for $10\ \mathrm{TeV} < E < 10^4\ \mathrm{TeV}$. This form is within the range of current theoretical predictions. Neutrino energies in the simulations (done by Monte Carlo) varied from $10 - 10^4$ TeV. The practical lower limit of energy is between 10 and 50 TeV, since below this value the Earth is essentially transparent. The practical upper limit is between 10^3 and 10^4 TeV, beyond which the Earth is essentially opaque, and fluxes are expected to be too small for tomography.

We assumed 1000 receivers operating for 2 years, or 200 receivers operating for 10 years. The error bars in the plots reflect the statistical errors in density determination for different flux assumptions. To a good approximation the statistical errors scale with the number of receivers, so that 10 times fewer receivers with the same flux is equivalent to the assumed number of receivers with 10 times smaller flux. The final extracted density profiles for two cases are shown in Figs. (1,2). The step between the core and lower mantle is very well resolved in Fig. (1). However the inner core is not resolved, partly because we did not make a special effort to bin events in a way that might bring out this feature. The inner core is difficult to resolve in any event, because it subtends a rather small solid angle. The total mass is consistent, so that Neutrinos can "weigh the Earth". On the other hand, since the mass is well known, then by iteration the boundary condition at the "crust" can be deduced.

There are certainly many uncertainties in going from our model calculations to realistic experimental design. Only further study can resolve this. During a period of a few years to a decade, a $KM3$ neutrino telescope will be fulfilling a primary mission as a fundamentally new kind of instrument for observing the cosmos. With the same kind of detector, neutrino tomography could also provide important and independent information about the Earth's interior. Further details are given in Jain, Ralston and Frichter (1999).

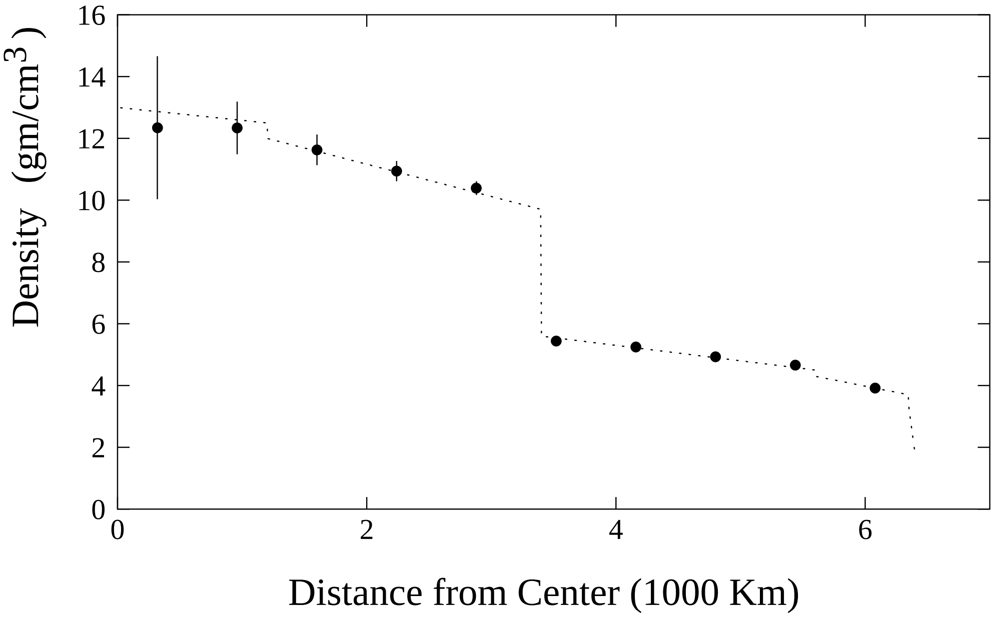

Figure 1: The extracted nucleon density using ten radial bins along with the statistical errors. The PREM model for the Earth's density, dashed curve, was used to generate data. The step between the core and lower mantle is very well resolved, while the difference between the inner and outer cores is not.

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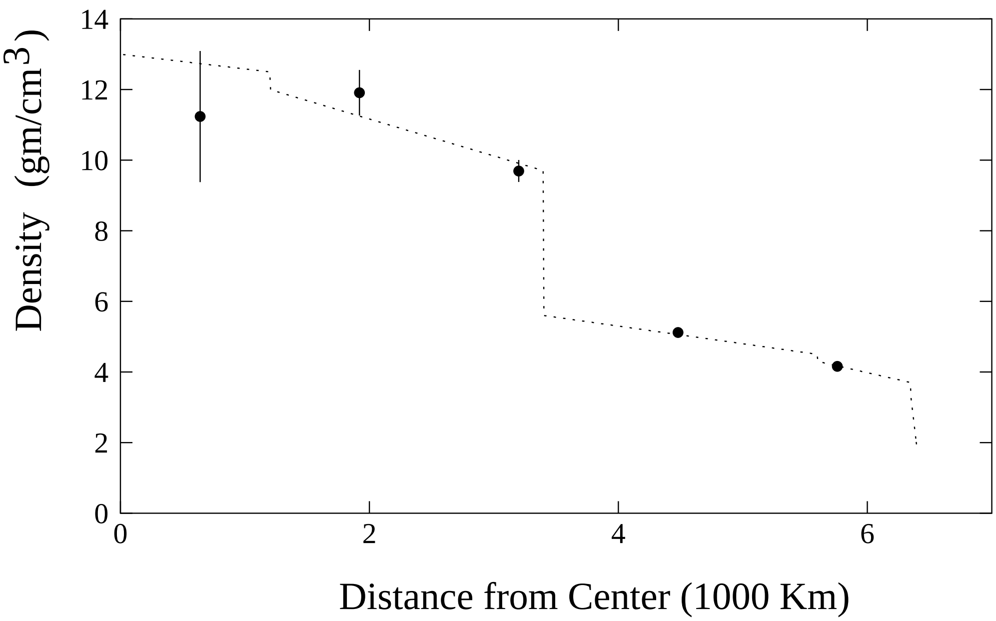

Figure 2: The extracted density using five radial bins along with the statistical errors, assuming one tenth the event rate compared to Fig. 1. The step between the core and lower mantle remains well resolved.